Summary Information Page

Project Title

Improving WRF/CMAQ Model Performance using Satellite Data Assimilation Technique for the Uintah Basin.

Applicant Information

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Funding Requested

$38,392(To be matched by an additional $15,000 from other funding sources.)

Project Period

July 01 – December 31, 2019

Abstract

In this proposed project, we will investigate the applicability of Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data assimilation to improve WRF/CMAQ model performance for the Uintah Basin. We will also examine WRF model performance with two land surface model setups that have different level of utilizing high resolution land cover data. Works to be performed include modifying WRF/CMAQ model source codes for incorporating MODIS data, and performing sensitivities simulations for one winter and one summer episodes in 2011 to evaluate the effect of MODIS data assimilations and land surface models on WRF/CMAQ performances. This study serves as our first step into exploring the applicability of satellite data assimilation technique and the potential benefits of advance satellite products, such as those of the Landsat and Sentinel.

1. Basis and Rationale

At Bingham Research Center (BRC) we have been working on improving meteorological model (WRF) using the data assimilation technique (Lyman et al., 2018; Tran et al., 2018). Although we have been successful improving WRF model performance with this technique, the caveat is that availability of observational data is limited, especially for data on the vertical structure of the atmosphere. We are actively developing and have deployed monitoring instruments for modeling data assimilation purpose for winter 2018-2019 and onwards. Obviously, limitation in observational data still heavily hinders modeling data assimilation for the past years.

Another front of improving meteorological model performance is by improving the model parameterizations, i.e., the way the model employs numerical equations and empirical parameters to simulate physical processes over land, water and in the atmosphere. In this project proposal, we particularly focus on improving WRF performance in simulating the physical processes occur in the interface of land and the atmosphere.

Land surface characteristics determine many physical processes occurring in the planetary boundary layer (PBL) and play an important role in atmospheric models from large scale to regional and mesoscale (Rowntree, 1983; Rowntree and Bolton, 1983; Avissar and Pielke, 1989; Chen and Avissar, 1994a; b; Chen and Dudhia, 2001). The transports of energy between land surface and PBL, upward short-wave and long-wave radiations, sensible and latent heat fluxes, are often simulated by the use of land surface model (LSM). For example, the state-of-art and widely used Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) include several LSMs including the unified Noah (Tewari et al., 2004), Rapid Update Cycle (Benjamin et al., 2004), Pleim-Xiu (Pleim and Xiu, 1995; Xiu and Pleim, 2001) and others. The ability in accurate short-term forecasts of hazardous weather events, such as convective storm, icing, low visibility, could have life-saving meaning. As WRF is also commonly used in coupled with an air quality model, such as the Community Model-3 Air Quality (CMAQ) model (Byun and Schere, 2006), the performance of WRF heavily drives the CMAQ's performance which determine, for example, how timely a health-related air quality advisory could be made to the public.

Among land surface parameters, Leaf Area Index (LAI) and vegetation fraction (VF, or analogously FPAR - fraction of absorbed photosynthetically active radiation) are crucial parameter for determining energy fluxes at the ground surface and depositions of various atmospheric gases and particles. By default WRF LSMs employ predefined vegetation and land use parameters from look-up tables or from out-of-date monthly average satellite vegetation parameters (Hong et al., 2009; Ran et al., 2010) which have limitations in capturing seasonal landscape changes (e.g., phenology and albedo) and disturbances (e.g., fires, storm damages, urban development). For example, Ran et al. (2015) demonstrated that WRF simulations with

Pleim-Xiu (PX) LSM generally overestimated vegetation fraction in comparison with MODIS data.

Recent WRF/CMAQ simulations for winter ozone in the Uintah Basin showed that an arbitrary LAI reduction led to noticeable increase in simulated ozone concentrations (Matichuk et al., 2017). Figure 1 shows examples of LAI as measured by MODIS and as calculated by WRF model. WRF tends to underestimate LAI over high elevation areas but highly overestimate in low elevation areas and particularly the Uintah Basin. This misrepresentation of the land surface characteristics potentially hinders the model performances in simulating the atmosphere.

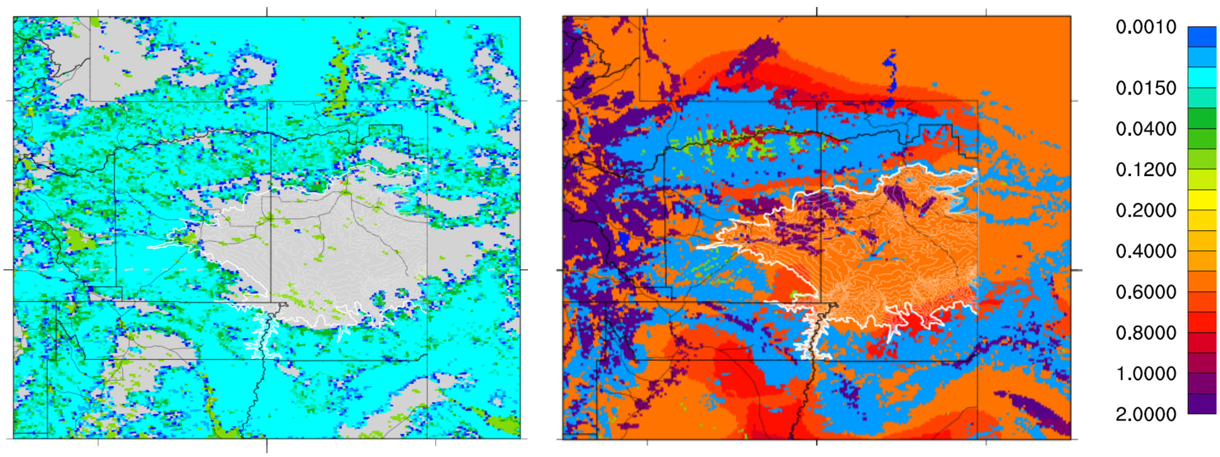

Figure 1. Comparison of LAI as measured by MODIS (left) and as calculated by WRF model (right) in 02 February 2013. In this Figure, the white polygon depicts the Uintah Basin ozone nonattainment area. LAI from MODIS data was calculated as LAI/FPAR as discussed in (Ran et al., 2015).

Another issue in poor representation of land surface characteristic is the serious outdate in land-use dataset for WRF model. Earlier version of WRF model still utilizes USGS Global Land Cover Characterization land-use dataset which was developed for base year 1992-1993, or MODIS land-use dataset which was developed for base year 2004. Because of this issue, WRF model users commonly had to modify land-use dataset with latest data for their simulation domain to reflect the actual land surface characteristics, e.g., Crosman and Foster (2017). However, such modifications also depend on readily available land-use dataset which may be also outdated and does not well represent the current land-use characteristics. Even though the National Land Cover Database (NLCD) 2006 and 2011 have been made available to user in recent WRF version, Crosman and Foster (2017) revealed that even the 2011 overestimated the Great Salt Lake area for which manual fixes to the land-use data were required to correctly characterize the Great Salt Lake.

Applications of satellite data in improving LSM model performance have been performed using LAI and FPAR daily and annual data retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data (Moore et al., 2010; Ran et al., 2015; Ran et al., 2016). Moore et al. (2010) demonstrated improvements in estimations of land surface temperature both temporally and spatially for model simulation over East Africa with the assimilations of MODIS dynamic LAI and VF. Ran et al. (2015) incorporated LAI and FPAR inputs from MODIS data into WRF/CMAQ model to provide a better representation of spatial and temporal variation of vegetation cover over the arid western U.S. They also incorporated MODIS albedo into WRF model to replace for the calculated albedo performed by the Pleim-Xiu

LSM (Pleim and Xiu, 1995; Xiu and Pleim, 2001). Such treatments led to reducing error and biases in moisture but larger errors in temperature estimates. Additionally, simulated O_3 increased as the results of reducing dry deposition velocity due to smaller MODIS LAI and vegetation fraction values (Ran et al., 2015). Ran et al. (2016) applied the above MODIS data treatment for a year-long WRF/CMAQ simulations for 2006 over the North American 12-km domain. They reported improvements in 2-m temperature and moisture estimates, and increase in O_3 concentration due to the MODIS reduced vegetation covers.

We are proposing to investigate assimilating satellite data, particularly the MODIS data, for improving WRF/CMAQ model performance for the Uintah Basin. This study serves as our first step into exploring the applicability of satellite data assimilation technique and the potential benefits of advance satellite products, such as those of the Landsat (https://landsat.gsfc.nasa.gov/data/) and Sentinel (https://sentinel.esa.int/web/sentinel/missions) for atmospheric research.

2. Technical Approach

2.1. Performing MODIS data assimilations to WRF/CMAQ model and model performance evaluation

Although satellite data assimilation has been implemented to WRF LSMs as discussed in section 1, such techniques have not been made available to WRF model released to general users. This is because data assimilation varies with type of data set to be used, and the target WRF module to be incorporated to. Therefore, such data implementation required custom modifications to WRF modules in case by case basis.

We will apply the approach presented in Ran et al. (2015) for ingesting MODIS data into WRF/CMAQ. More refined MODIS data products have become available after 2015 and thus we will use the improved version of the corresponding MODIS datasets that were used in Ran et al. (2015). Particularly, we will use the gap-filled and smooth MODIS Collection 6 Level-4 LAI and FPAR data (MCD15A3H) which available every 4 days at 500 m resolution for the WRF simulations. For surface albedo, we will utilize the MODIS bidirectional reflectance distribution BRDF/Albedo Parameters Level-3 (MCD43A1) and the corresponding BRDF/Albedo Quality Level-3 (MCD43A2) dataset, both are available daily and in 500 m resolution. Method for calculating diurnal albedos from the daily MODIS BRDF/Albedo is discussed in (Ran et al., 2015), and in summary, is determined from the following equations:

$$\alpha_{BSA}(\theta_{Sun},\lambda) = f_{iso}(\lambda)g_{iso}(\theta_{Sun}) + f_{vol}(\lambda)g_{vol}(\theta_{Sun}) + f_{geo}(\lambda)g_{geo}(\theta_{Sun})$$

$$\alpha_{WSA}(\theta_{Sun},\lambda) = f_{iso}(\lambda)g_{3iso} + f_{vol}(\lambda)g_{3vol} + f_{geo}(\lambda)g_{3geo}$$

$$\alpha_{BLUE} = \alpha_{BSA}(\theta_{Sun})(1 - D) + \alpha_{WSA}D$$

where α_{BSA}, α_{WSA}, and α_{BLUE} are black sky, white sky and blue sky albedos, respectively, and are the functions of solar zenith angle (θ_{Sun}) and wavelength (λ); *D* is diffuse radiation fraction; the three parameters f_{iso}, f_{vol} and f_{geo} characterizing isotropic, volumetric and geometric scatterings are obtained from MCD43A1 dataset; g_{iso}, g_{vol} and g_{geo} are determined from constants and θ_{Sun} using simple polynomial equations discussed in Lucht et al. (2000).

For the purpose of this project proposal, we refer the processed MODIS input dataset described above as real time MODIS data. We will re-grid this real time MODIS dataset at 500 m resolution into 1.3 km resolution model domain (see descriptions in section 2.3). We have developed software based on the Earth System Modeling Framework (ESMF;

https://www.earthsystemcog.org/projects/esmf/regridding) that allow us to perform upscaling or downscaling re-gridding dataset from different grid structure and resolution.

In standard WRF simulations, LAI, FPAR and albedo are calculated by WRF Preprocessing System (WPS) from the monthly averaged MODIS 2001-2010 climatological dataset. We will modify WRF source codes that allows WRF to replace the WPS's calculated values with real time MODIS data. The modified WRF will also allow writing LAI, FPAR and albedo into appropriate output format that can be used by CMAQ dry deposition and photolysis modules.

2.2. Sensitivity simulations with Noah and PX LSMs

The Noah LSM have been using in our WRF simulations for Uintah Basin Ozone Study (UBOS) and the Air Resource Management Strategy (ARMS) modeling study (see descriptions in section 2.3). In standard model configuration which is currently applied in BRC's WRF simulations, Noah LSM assumes the dominant land cover type in each grid-cell as the land cover for that grid-cell and therefore ignores the subgrid-scale heterogeneity of land cover. Since WRF v 3.6, sub-tiling option is made available so that modeler can specify number of land cover type to be considered by Noah LSM (WRF User's Guide, 2018).

The PX LSM uses fractional land cover type and thus is able to utilize the high-resolution land cover data such as the 500 m MODIS or the 30 m National Land Cover Database (NLCD) (Ran et al., 2015). More noticeably, PX LSM was developed for retrospective simulations and it allows soil nudging option where observational 2-m temperature and water vapor mixing ratio are utilized for deep soil moisture and temperature nudging (WRF User's Guide, 2018).

Because of the distinct difference between Noah and PX LSMs, we will perform WRF sensitivity simulations using Noah LSM with sub-tiling option (*sf_surface_mosaic = 1*) and PX LSM with reanalysis nudging. We will compare WRF performances in these two configurations and compare them with WRF performance with standard Noah configuration (*sf_surface_mosaic = 0*)

With the above sensitivity simulations, we will examine whether WRF model's performance improves with different LSM configurations, and with high resolution land cover data.

2.3. WRF/CMAQ model configurations

We are performing the Air Resource Management Strategy (ARMS) modeling study for the Utah BLM for base year 2011. Tables 1, 2 and 3 summarize grid definitions for the WRF Preprocessor System (WPS), grid configuration, topographical, land use, boundary/initial conditions and physics options for non-winter and winter configurations. Figure 2 indicates the 2017 ARMS WRF and CAMx domains.

For this project, we will perform simulations using the modified version of WRF/CMAQ for MODIS data assimilation based on the ARMS WRF/CAMx model configurations presented in this section. Furthermore, we will only perform and analyze results of WRF/CMAQ simulations for the 1.3 km inner domain (Domain 3 in Table 2) of which the boundary conditions will be assimilated from the outer ARMS domains. With this approach we will able to leverage the input data processing (e.g., boundary and initial concentrations, emissions) that we perform for the ARMS modeling study for this project.

We will perform simulations for one winter episode (January 20 – February 20, 2011) and one summer episode (June 1 – 30, 2011). We will examine WRF/CMAQ performance in winter and summer episode to understand the impact of MODIS data assimilation with differences in vegetation covers.

Table 1. Grid definitions for WRF Preprocessor System (WPS version 3.9)

Parameter name	Parameter value
Projection	Lambert conformal
Reference latitude	40 N
Reference longitude	-109.5 W
truelat1	33
truelat2 =	45
stand_lon =	-97

Table 2. WRF model grid configurations and topographical, land use and initial/boundary conditions.

	Domain 1	Domain 2	Domain 3 (*)
Grid Size (x,y)	200 x 190	250 x 250 (20 grid cell buffer in all direction for CAMx domain)	298x322 (20 grid cell buffer in all direction for CAMx domain)
Vertical levels	37	37	37
Vertica grid spacing	12-16 m in boundary-layer	12-16 m in boundary-layer	12-16 m in boundary-layer
Horizontal resolution (km)	12	4	1.33
Model time step (s)	30	10	3.33
Topographic dataset	USGS GTOPO30	USGS GTOPO30	USGS GTOPO30
Land use data set	NLCD2011 modified 9s	NLCD2011 modified 9s	NLCD2011 modified 9s
Initial and boundary conditions	NAM-12km	Continuous updates nested from 12km domain	Continuous updates nested from 4km domain
Top and Bottom Boundary Conditions	- Top: Rayleigh dampening for the vertical velocity - Bottom: physical, non free-slip option	- Top: Rayleigh dampening for the vertical velocity - Bottom: physical, non free-slip option	- Top: Rayleigh dampening for the vertical velocity - Bottom: physical, non free-slip option
Veg parm table variables modified for winter simulations (*)	SNUP, MAXALB	SNUP, MAXALB	SNUP, MAXALB
Snow cover initialization (*)	- SNODAS - Linear obs analysis for Uintah and Great Salt Lake Basin (Neemann et al, 2015; Foster et al., 2017)	- SNODAS - Linear obs analysis for Uintah and Great Salt Lake Basin (Neemann et al, 2015; Foster et al., 2017)	- SNODAS - Linear obs analysis for Uintah and Great Salt Lake Basin (Neemann et al, 2015; Foster et al., 2017)

(*) applied to winter simulations only

Table 3. Physics options used in the WRF Version 3.9

WRF Treatment	Option Selected
Microphysics	Thompson
Longwave Radiation	RRTMG
Shortwave Radiation	RRTMG
Land Surface Model (LSM)	NOAH
Planetary Boundary Layer (PBL) scheme	YSU for non-winter simulations MYJ for winter simulations

Cumulus parameterization	Kain-Fritsch in the 12 km domains. None in the 4 and 1.3 km domain.
Analysis nudging	- Nudging applied to winds, temperature and moisture in the 12 km domains. - For winter simulations nudging applied to moisture in all domains.
Observation Nudging	Nudging applied to surface wind and temperature in the 4 and 1.3 km domain

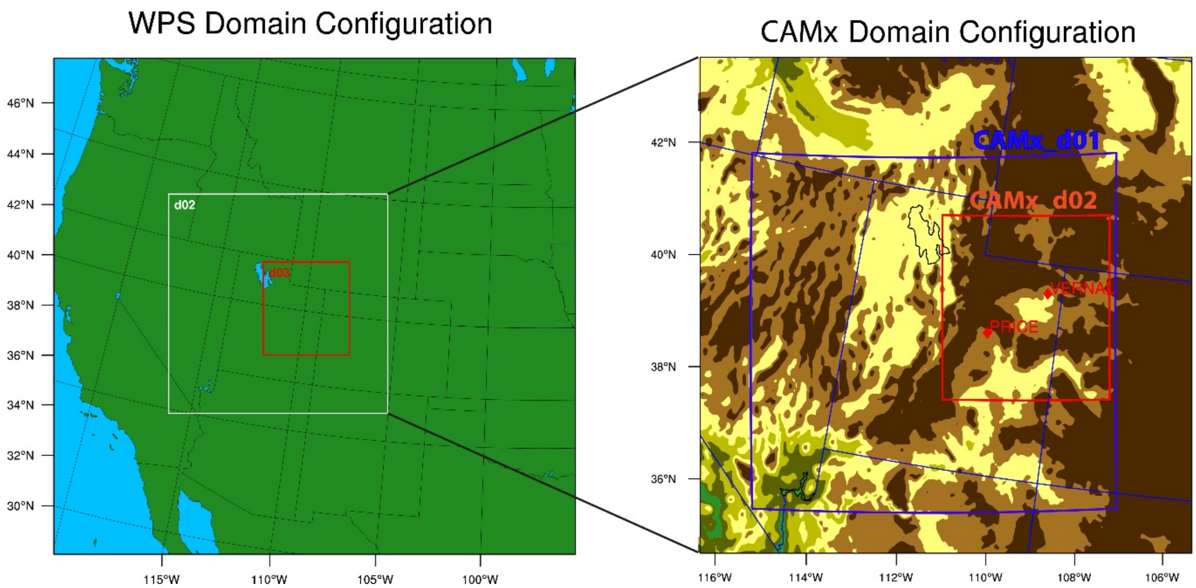

Figure 2. WRF (left) and CAMx (right) domain of the 2017 ARMS

Methods for WRF model evaluation are similar to the methods that we are applying for the ARMS study. Specifically, we will follow the combination of qualitative and quantitative analyses as in 3SAQS 2011a (UNC and ENVIRON, 2014) for non-winter months and WAQS 2011b (Bowden et al., 2015) for winter months. The observed database for winds, temperature, and water mixing ratio used in this analysis include the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL) Meteorological Assimilation Data Ingest System (MADIS). We will conduct additional evaluations as in (Tran et al., 2018) focusing on WRF's ability to capture the inversion layer structure over the Uintah Basin in 2011. Observations will be collected from both national (e.g., NOAA), state (UDAQ) and local agencies (e.g., Bingham Research Center).

For CMAQ model evaluation, we will focus on CMAQ ability in simulating ozone, nitrogen oxides (NO and NO_2), and several volatile organic compounds. We will also analyze ozone dry depositions under different scenarios including with and without MODIS data assimilation, and Noah vs. PX LSM.

3. Expected Outputs and Outcomes

Through this project, applicability of satellite data assimilation for improving meteorological and photochemical models performance for Utah, with focus on the Uintah Basin, is investigated. This project also serves as the first step in understanding the benefit of using products from advanced satellite platforms, such as Landsat and Sentinel, for air quality study.

4. Deliverables

- Model data: including processed input MODIS data, inputs and outputs of WRF/CMAQ model. Due to large storage space of the data, it will be hosted in USU data archive and is shareable to UDAQ and the public (with UDAQ's approval). We commit to retain the dataset for at least ten years upon completing this project.
- Quarterly reports: two quarterly reports will be delivered by 30 September 2019 and 31 December 2019.
- Final Technical Report: the final report will be produced and submitted to UDAQ within 30 days after completion of the project (due on 31 January 2020).
- Oral or poster presentation at the Utah Science for Solution in 2020.

5. Schedule

BRC will perform the following activities throughout the project performance period from July to December 2019 (6 months) as shown in Table 4. The final report and final datasets will be due on 31 January 2020.

Table 4. Gantt chart showing a timeline for the project.

TASK	JUL				AUG				SEP				OCT				NOV				DEC			
Download and process MODIS data	■	■	■	■																				
Modify WRF/CMAQ source codes, test and debug					■	■	■	■																
Perform WRF simulations with MODIS data assimilation								■	■	■	■	■												
Perform WRF simulations for LSM sensitivity study													■	■	■	■								
Perform CMAQ simulations for each of the sensitivity/scenarios											■	■	■	■	■	■	■	■						
WRF model performance evaluation										■	■	■	■	■	■	■	■	■	■	■				
CMAQ model performance evaluation												■	■	■	■	■	■	■	■	■	■			
Technical analysis and Quarterly Reports												■						■	■	■	■	■	■	■

6. Budget

Table 5 shows a summary of the requested budget which include:

- The budget includes funding for three months of salaries each for two BRC's researchers
- Fringe benefits are calculated at 46.50% of salary costs.
- Cost for material (data storage space): $120/TB x 2TB
- Indirect cost (Facilities and Administration) 10% of total direct cost.

Of the total $53,392 estimated expense for this project, $15,000 will be provided from BRC's legistrative funding (matching fund), and the remaining $38,392 is requested from UDAQ funding.

Table 2. Budget summary.

CATEGORY	COST
Salaries Huy Tran ($18,033) Trang Tran ($14,935)	$32,968
Fringe benefits (46.5%)	$15,330
Material (2TB of data storage)	$240
Facilities and Administration Cost (10%)	$4,854
TOTAL	**$53,392**
Funding secured from BRC's legistrative fund	**$15,000**
Awarded fund from UDAQ	**$38,392**

Personnel Roles and Responsibilities

Dr. Huy Tran – Senior Research Scientist at BRC: is the principal investigator of this project. He will be responsible for the MODIS data processing, modifications of model source codes, CMAQ model configuration, performing CMAQ simulations and performance evaluation, final data analyses and report. Dr. Tran has extensive experience in software development using various programing language including python, java, Fortran, R and visual basic.

Dr. Trang Tran – Senior Research Scientist at BRC: she will be responsible for developing WRF model configurations, performing WRF sensitivity tests and model evaluation. Dr. Tran has extensive knowledge in data assimilation technique, programing, data analysis and serves as the key WRF modeler at BRC.

Although no graduate or undergraduate student is participating in this project proposal, we may recruit an undergraduate/graduate student to work on this project through the Anadarko Air Quality Research Fellowship (https://binghamresearch.usu.edu/studentfellowship/) if the student is interested in this project.

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